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A RIG FOR TESTING THE SOFT SOIL PERFORMANCE OF TRACK SYSTEMS

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INTRODUCTION

For a given level of performance the track and suspension system of a military tracked vehicle must be as light and compact as possible to maximise weight and volume available for crew and payload (armour protection, weapon and communication systems, ammunition, fuel, etc). Although track systems have been used on military vehicles for some seventy years methods for predicting their performance in soft soil - and actual performance measurements - are limited and, even with its shortcomings, the nominal ground pressure term* remains the performance comparator most commonly used by vehicle designers. This is partly because of the complexity of devising, proving and using improved methods and partly because military vehicle testing and training areas tend to be on sandy frictional soils where tracked vehicles rarely exhibit mobility problems. Operational areas are likely to include silty and clay soils where differences in track system design will affect performance to a much greater degree. If an improved track/soil model was available overall automotive system performance models could also be improved and designers would be able to make more rational choices between often conflicting requirements - for example:-

- increasing the number of wheels should improve soft soil performance and also reduce sponson height but increase cost and weight.

- increasing wheel diameter is likely to improve soft soil performance but increase sponson height, weight and cost.

- increasing track width should improve soft soil performance and reduce bush loading but will reduce space available inside the vehicle.

- increasing track pitch is likely to improve soft soil perfromance and reduce track weight but increase the level of vibration due to chordal action and reduce the life of track bushings.

- increasing track contact length is likely to improve straight line soft soil performance but may increase slewing moments required to steer the track.

The important soft soil performance parameters for a military tracked vehicle are generally:-

- Limiting go/no go soil strength - this defines the areas of terrain generally accessible to a vehicle under particular soil and weather conditions.

* NGP = vehicle weight/track width x track contact length x number of tracks.

- Tractive rolling resistance - the lower this is the greater the potential speed and range of a vehicle. Rolling resistance is usually considered divided between internal and external components - the internal being the proportion due to sprocket engagement, pin, bearing and seal friction, rubber hysteresis losses (road wheels, idlers, bushes, pads, return rollers), horn rubbing etc., and the external component due to work done in soil deformation.

- Net traction is required to enable a vehicle to climb gradients, accelerate and, for a skid steered vehicle, to steer although the straight line traction considered here will only give a comparative indication of traction required to steer a vehicle. The development of external traction (or drawbar pull) is important for towing dead vehicles, bulldozing, mine clearing, etc.

- The development of high tractive efficiency under traction conditions is important in that it affects vehicle acceleration and speed on gradients but is not as important for overall fuel efficiency as on, for example, an agricultural tractor used for ploughing.

SOIL/TRACK SYSTEM PERFORMANCE MODELS

A number of theoretical, semi-empirical or totally empirical models of soil/tracked vehicle performance exist although details of validation tests with most of these models are generally sparse. They include:-

1. The WES VCI method (Ref 1) which is a totally empirical method based on in-soil measurements of vehicle performance. Cone Index (CI), or Rating Cone Index (RCI), is used for describing soil strength. The method applies to cohesive fine grained soils and the first stage in using it is to compute a Mobility Index (MI) from vehicle parameters. In essence MI takes the form

$$MI = \frac{50\ kW}{b^2 \ell} + \frac{W}{10\ nbp}$$

where W = vehicle weight (lbf)
b = track width (ins)
ℓ = length of track on ground (ins)
n = total number of road wheels
p = track pitch (ins)
k depends on vehicle weight

Various other correcting factors for ground clearance, power/weight ratio, transmission type etc., are also included in MI but have a relatively small influence on its value. The second term looks promising in that it has units of pressure and appears to make allowance for the peaks of pressure which occur under road wheels. The first term however has the rather inappropriate units (for a cohesive soil/vehicle model) of specific weight and appears to give undue benefit to wide tracks. If figures for a typical heavy armoured vehicle are inserted into the relationship we get

$$MI = 100 + 7$$

i.e. the first term with its rather unsatisfactory form is by far the dominant one. The limiting go/no go soil strength VCI (Vehicle Cone Index) can then be estimated from an empirical relationship and is approximately proportional to MI. Drawbar pull and rolling resistance in soil of a particular strength can be estimated from simple relationships based on 'excess' RCI (actual RCI - VCI).

2. The Bekker method (2) uses the well known two part Bevameter instrument to measure soil values. A plate sinkage test is used to simulate vehicle sinkage and predict rolling resistance. A ring shear test is used to simulate and predict gross traction. Net traction is computed as the difference between gross traction and rolling resistance. The track is assumed to act as a rigid flat plate which may be reasonable for a crawler tractor with closely spaced wheels but is unlikely to be so for the usual type of military vehicle sprung track system. Although some impressive looking predictive equations have been published, details of validation studies of the method are limited.

3. The method is now being considerably extended by Wong (3) who still uses the basic bevameter instrument for measuring soil properties but in a vehicle mounted form with automatic data processing. The pressure sinkage relationship under repetitive loading and the slip sinkage characteristics of the terrain are also measured. In modelling the soil/vehicle interaction the track is assumed equivalent to a flexible and inextensible belt. Positions and diameters of roadwheels, sprocket, idler and support rollers are specified. Using the measured soil characteristics a system of equations are set up for the equilibrium of forces and moments acting on the track system and for conservation of track length. The deflected shape of the track and track/soil contact stresses are computed. Only a limited amount of data on validation studies have so far been published but the system shows promise especially if computer implementation is relatively simple and a range of 'standardised' soil values can be made available for use be designers. The lack of track link pitch as a vehicle parameter can be questioned since this has been shown to be a significant factor (4) as can the assumption that the road wheels are rigidly attached to the body although it would appear relatively easy to include suspension deflection effects.

4. Turnage has performed some laboratory tests with a modular track rig (5) in dry sands and near saturated clays. Cone Index was used to measure soil strength. The track was a belt type with bolted on shoes. Track contact length and width, and spacing and number of wheels could be altered. Most of the test work was with the sands but a preliminary dimensionless prediction term for clays was also suggested in the form

$$\frac{CI\,b\ell}{W}\left(\frac{W}{W_{max}}\right)^{0.5}$$

W = Total load on track

Wmax = Load to cause bogies to bottom out on suspension

ie $\frac{CI}{NCP}$ $\left(\frac{W}{Wmax}\right)^{0.5}$

$\left(\frac{W}{Wmax}\right)^{0.5}$ is apparently a term to allow for the effects of load concentrations under the wheels but its derivation is not easy to follow.

5. In 1972 Rowland evolved the mean maximum pressure (MMP) term (4)

$$MMP = \frac{1.26W}{nbe\ (pd)^{0.5}}$$

d = diameter of road wheels
e = ratio, actual area of track link/nominal area, pb.

which correlated well with measured in soil pressure peaks under road wheels. Rowland postulated that MMP would be expected to give a guide to the soft soil behaviour of tracked vehicles and showed that it was linearly related to limiting go/no go soil strength (CI or RCI) in clay and organic soils. He also produced a relationship for external rolling resistance in clay soils (6)

$$C_{RE} = 0.28 \left(\frac{MMP}{CI}\right)^{1.95}$$

where C_{RE} = coefficient of external rolling resistance

and further hypothesised that $\frac{CI}{MMP}$ could be used as a describing mobility number for track systems and in the form $N_C = 2.6 \left(\frac{CI}{MMP}\right)^{0.72}$ could be comparable to the WES pneumatic tyre mobility numbers and their predictive performance relationships (7).

THE MVEE MOBILE TESTER

A prime requirement of this investigation was some means of obtaining accurate in soil performance measurements for a variety of track system configurations. It was decided that a mobile tester of the type used by NIAE and others was the most adaptable and cost effective way of obtaining this information. Laboratory scale model testing can give useful information but would still need to be correlated with full scale testing. Full scale laboratory testing in soil pits presents formidable problems of soil processing especially with clay soils and has now been abandoned at MVEE. There are various experimental difficulties with using a vehicle to measure in soil performance - controlling slip for example - and extensive modifications would be required to fit different track system configurations to the vehicle.

The MVEE mobile tester (Fig 1) is based on a crawler chassis to enable it operate effectively in weaker soils and is capable of testing wheels (8) as well as the modular track rig described here. The track rig is carried in an arch frame and connected to the tester by parallelogram links which can also lift the rig clear of the ground when manoeuvring. Hydrostatic drive motors are accommodated within the

track rig and are connected to the track sprockets via roller chains. The track rig is normally freely pivoted in pitch to simulate straight running of a two track skid steered vehicle although pitch restraint can be applied to the rig to simulate certain types of articulated, wagon steer and half track vehicle. The position of the rig to frame pivot point can be adjusted to model different c.g. positions and 'traction centre' heights.

The track rig is 3.2 m from idler to sprocket centre with a nominal dimension of 2.0 m between front and rear wheels. The maximum road wheel size is 0.61 m dia and 2, 3 or 4 of these can be fitted. Up to eight 0.25 m dia wheels can be used. 0.36 m and 0.43 m dia wheels can also be fitted in various 2, 3, 4, 5 and 6 wheel configurations. A variety of link tracks up to a maximum width of 0.61 m can be used. A simple band track is also available.

The wheels are carried on pivoted balance beams to accommodate terrain roughness. When the rig was designed consideration was given to the use of an individual wheel sprung suspension but space was not available in the rig to accommodate the springs and the wide range of individual wheel loadings would have required a range of springs of various rates. The use of load equalising balance beams is a reasonable compromise - compared to a sprung suspension weight transfer is reacted between a forward set of equally loaded wheels and a rearward set of equally loaded wheels. With a sprung suspension weight transfer is generally proportional to the distance from the 'spring centre' (usually near the centre of the vehicle) and spring deflections will also alter the approach and departure angles of the track. The rig can be turned round to provide a forward or rear drive sprocket and approach and departure angles can be adjusted. Total ground load can be varied by means of ballast weights between approx 25 kN and 55 kN.

Tractive forces from the rig are measured by a pair of horizontal transducers. Sprocket torque is measured by a strain gauged shaft within the sprocket hub which carries torque between the chain sprockets and track sprockets. Signals are fed out via slip ring boxes. Sprocket speed is measured by a toothed ring and inductive pick up within the hub. Although other methods have been used forward speed is now measured by a toothed ring on the tester sprocket, tests having shown tester track slip to be very small under most conditions.

EXPERIMENTAL PROCEDURE

For the trials reported here the rig was used in its rear drive configuration with the external pivot point at mid-wheelbase and at a height above ground to give approximately the same ratio of traction centre height to wheelbase as c.g. height to wheelbase on a typical tracked armoured vehicle. Tests were generally performed at a vertical load of 55 kN although some tests were run at half this load. The following track system configurations were used:

No of wheels	Dia of wheels	Track (see Fig 2)			
		Type	width, b	pitch, p	Area ratio, a
8	0.254	A	0.343	0.117	0.831
4	0.610	A			
		B*	0.343	0.117	0.831
		C	0.343	0.230	0.831
		D	0.425	0.116	0.672
		E	0.288	0.116	0.814
	0.432	A			
		B			
	0.254	A			
2	0.610	A			

* Track A less rubber pads.

All tracks rubber bushed except track C which is dry pinned.

Tests were performed by the progressive slip method. The track speed was held nominally constant and the parent vehicle speed varied to give a range of slips from approx -20% to +100% with slow transition through the important -5 to +30% slip region. Measurements of net thrust, sprocket input torque, sprocket speed and forward speed were recorded on magnetic tape.

Runs were made at two, (sometimes three) track tensions, with at least 12 runs per track configuration.

Soil strength measurements were made by cone penetrometer - at least 6 measurements per run - with a concentration of measurements in to 0 to 20% slip region. In rut measurements were also made.

Analysis

The magnetic tape recordings were played via filters and A/D converters into a computer for analysis and graph plotting. The tractive effort recordings were corrected for tester longitudinal acceleration. Gross traction P_G, net thrust or traction P_T, tractive rolling resistance R_T, tractive efficiency η, and slip s were computed as follows:

$$P_G = \frac{T}{r}$$ where T = sprocket torque, r = effective sprocket radius

$$R_T = P_G - P_T$$

$$\eta = \frac{P_T v}{T\omega}$$ when v = forward speed, ω = sprocket angular speed

$$s = \frac{\omega r - v}{\omega r}$$

P_G, P_T and R_T were divided by track weight to give the coefficients of gross traction C_G, net traction C_T and tractive rolling resistance C_R. C_G, C_T, C_R and η were plotted against slip.

RESULTS

Results from two test sites are reported here - both sugar beet fields after harvesting. Soil moisture content on both sites was unseasonably low giving comparatively high soil strengths.

Site A

The soil was a very silty medium/fine sand with over 30% silt or clay (USCS Classification SM/SC). Moisture content was around 20% giving average cone index values of around 450 - 500 kPa in the 0-150 mm layer. Laboratory triaxial tests on a sample of the surface soil shows it to be mainly cohesive with some frictional properties ($\phi = 9°$).

Site B

The soil in this site was a clayey silt (USCS classification ML/ML-CL) with at least 50% silt or clay. Moisture content was around 29%. Average cone index values for the 0-150 mm layer were typically around 300 kPa.

Traction Curves

Typical traction curves from both sites are shown in Figs 3 and 4. High values of gross traction coefficient were obtained at Site A - in some cases exceeding 1.2. Traction coefficients were appreciable lower for Site B because of the weaker soil. A noticeable feature of the curves for Site A is the considerable increase in rolling resistance which occurs as traction develops. In some cases the coefficient of rolling resistance at 20% slip is over 3 times its value at the self propelled point. This considerable increase was somewhat unexpected and unlikely to be due increased internal resistance which would be comparatively small for rubber bushed tracks. For comparison, data for the rolling resistance/slip relationship of wheels was investigated. Rowland (9) reviewed available data and suggested empirical relationships:

For pneumatic tyres

$C_R = (1 + s)$

i.e. C_R proportional to slip and doubling between 0 and 100% slip and, for rigid cylindrical wheels

$C_R = (1 - 0.75s)$

i.e. rolling resistance actually reducing with slip. No such simple relationships are apparent for track systems, the rolling resistance being a function of traction and the track system configuration.

In a two track skid steered vehicle traction causes weight transfer from front to rear depending on the position of the 'traction centre', the wheel and track arrangement and wheelbase. A moving unsprung track system generally takes up a characteristic tail down pitch angle. At low traction this is due to progressive compression of the soil under the wheels. As traction increases the soil under the rear of the track will be subject to greater shear deformations due to slip. This will increase the likelihood of soil failure and extra sinkage under the rear of the track. The effect is sometimes referred to as slip sinkage.

With a sprung track system the frame or hull will take up an additional angle due to spring deflections. This will be increased by a raised sprocket (or idler if front driven) due to the vertical component of track (gross traction) force. Because the suspension will generally be considerably more compliant than the soil this component will also unload the soil under the rear wheel and thus increase loading still further on the adjacent wheels. The effect can be countered on front drive vehicles by means of so-called compensating idlers (Fig 5a). With a rear drive sprocket various arrangements are possible which interconnect a link between the final drive reduction gear and the rear wheel (Fig 5b). The extra cost and complication of these arrangements usually preclude their use although front mounted compensating idlers are quite widely used to counter vehicle nose dive when braking. Conversely soil offloading under end wheels may be beneficial when steering in reducing moments required to slew the track. An active suspension could be used to control soil normal forces under wheels.

In Fig 6 values of C_R are shown plotted against C_T as well as slip for 2, 4 and 8 wheel arrangements. It is noticeable that the increase in rolling resistance is much less marked with the two wheel arrangement where weight transfer is proportionately less than in the other arrangements and where track force does not off-load the rear wheel because it is rigidly attached to the track frame. The increase in rolling resistance thus appears to largely a function of weight transfer in the track system as traction increases. See Appendix for calculation of ground reaction loads.

Comparison of Different Configurations

All the arrangements were tested at a 'normal' tension (nominally 20% of weight on track system) and a 'tight' tension (nominally 30% of weight). High tension is sometimes thought to improve performance, especially in the go/no go region, presumably because of better 'bridging' effect between wheels although with sprung systems it also increases the tendency to offload the end wheels and hence increase loading on the remainder.

Averaging all the results from both sites gives the following values for C_{T20} and C_{RSP}

	Site A		Site B	
	Normal	Tight	Normal	Tight
C_{T20}	0.53	0.53	0.29	0.29
C_{RSP}	0.11	0.11	0.15	0.16

i.e. no significant difference between the pre-tensions.

Similarly one of the tracks was run without rubber track pads (track B in Fig 2) but again no clear trend was apparent - running without pads showing a slight increase in traction on one site and a slight decrease on the other. All the values of coefficient of traction at 20% slip C_{T20}, coefficient of rolling resistance at zero traction (the self propelled point) C_{RSP}, and the coefficient of rolling resistance at 20% slip C_{R20} were therefore averaged for each track system configuration neglecting track tension and the absence of track pads. These average values were then plotted against the dimensionless terms $CI/_{NCP}$ and $CI/_{M}$ to see if either can be used to adequately describe the measured data by means of empirical curves and form the basis of a simple tractive performance prediction system.

CI = average cone index in the 0-150 mm layer

$$M = \frac{W}{nbe\ (pd)^{0.5}}$$

The results are shown plotted in Figs 7 and 8.

The $CI/_{NCP}$ against C_{T20} plot (Fig 7a) shows an approximately linear relationship although with an appreciable amount of scatter in the low $CI/_{NCP}$ region and with no real indication of a limiting go/no-go value of $CI/_{NCP}$. The 8 wheel configuration is seen to perform well as does the long pitch track (C) at low $CI/_{NCP}$. The effect of wheel diameter is not readily apparent.

The plot of $CI/_{NCP}$ against C_{RSP} (Fig 7b) shows low resistance for the 8 wheel configuration at low $CI/_{NCP}$ and high resistance from the 2 wheel arrangement. The effects of wheel diameter and track pitch are not very apparent.

The $CI/_{M}$ against C_{T20} plot (Fig 8a) shows generally improved collapse of the data points and there is now an indication of a limiting go/no-go value of $CI/_{M}$ although no measurements are available for this region because of the comparatively firm soil conditions. Again the effects of wheel diameter and track pitch are not clear and in particular the long pitch track appears to 'underperform' with the weighting given to it in the M relationship. It was slightly unfortunate that on both test sites the long pitch track was tested on slightly firmer parts of the sites which makes it difficult to compare performance directly with the standard pitch track. The two wheel configuration is seen to perform comparatively well but this is probably because weight transfer effects

are comparatively small and there is little rise in rolling resistance with traction. A describing curve has been tentatively placed through the data points but no attempt has yet been made to ascribe any function to it.

The $CI/_M$ against C_{RSP} plot (Fig 8b) shows improved merging of the data points compared to $CI/_{NCP}$. C_R includes both external and internal components even though $CI/_M$ is attempting to describe only the external resistance. It is difficult to see how the two components can be easily separated. The usual assumption is that measurements of internal rolling resistance from hard road trials also apply to the off-load condition although recent tests at MVEE have shown that terrain roughness can markedly increase internal rolling resistance apart from the effects of soil packing in the track system. All the tracks were rubber bushed except the double pitch which was dry pinned. The internal resistance of dry pinned tracks are generally appreciably higher than equivalent rubber bushed ones and are also more sensitive to pretension and gross traction forces. Measurements on a vehicle have shown the low speed hard road resistance of the double pitch dry pinned track to be approx 0.015 greater than the standard rubber bushed one (both at normal tensions). The measured C_{RSP} data points have therefore been reduced by this amount. It is planned to use the tester to measure the hard road resistance of all the configurations to see if there are any marked differences between them.

Fig 9 shows $CI/_M$ plotted against C_{R20}. No particular relationship is apparent and in nearly all configurations the rolling resistance coefficient actually increases at higher values of $CI/_M$ due to higher traction and the effects of weight transfer.

Fig 10 shows $CI/_M$ plotted against peak tractive efficiency η_p. Generally quite good merging of the data points is indicated with η_p not exceeding 75-80% even at high values of $CI/_M$.

CONCLUSIONS

The mobile tester with modular track rig has proved a satisfactory way of gathering in field tractive performance data for track systems of different configurations.

The cohesive soil/track mobility number $CI/_M$ shows promise for forming the basis of a simple tracked vehicle performance prediction system but more data is required particularly in the important go/no go region where performance can be expected to be more sensitive to differences in track system configuration. At high traction consideration would also need to be given to weight transfer as affected by traction centre position, wheelbase and the departure angle of the track.

ACKNOWLEDGEMENTS

To Mr P Cox for organising and conducting trials.

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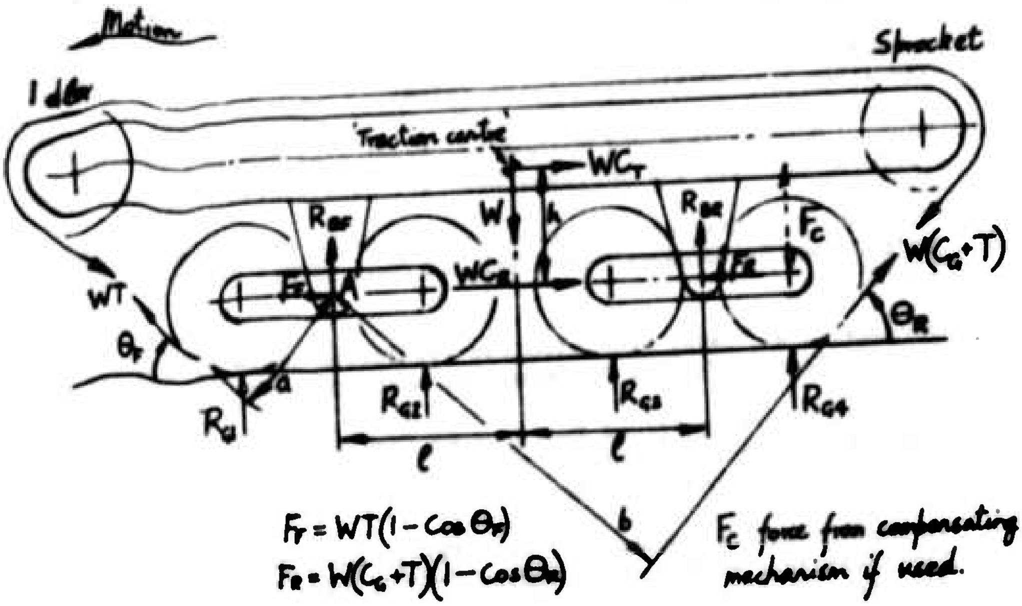
APPENDIX

The effect of traction forces on ground reaction loads.



Consider the 4 wheel equalising beam arrangement as used on the mobile tester track rig.

T = static track pretension, expressed as a ratio of vertical load on track system, and for a rear drive sprocket assumed to be maintained under traction conditions.

R_{G1}, R_{G2}, R_{G3}, R_{G4} = vertical ground reaction forces under wheels.

Since the wheels are free-rolling, rolling resistance will effectively act through the wheel centres.

Taking moments about A for forces acting on 'body'

$$WC_T h + W(C_G + T)b + Wl = R_{BR}\, 2l + WTa$$

$$R_{BR} = \frac{W(C_T h + (C_G + T)b + l - Ta)}{2l}$$

Resolving vertically for forces acting on wheel 4

$$R_{G4} + W\,(C_G + T)\,\sin\theta_R = \frac{R_{BR}}{2}$$

$$R_{G4} = \frac{W\,(C_T h + (C_G + T)b + \ell - Ta)}{4\ell} - W\,(C_G + T)\sin\theta_R$$

Similarly for wheel 3

$$R_{G3} = \frac{W(C_T h + (C_G + T)b + \ell - Ta)}{4\ell}$$

Inserting the average values of Site A, 0.61m dia wheels, track A/B

C_{T20}	= 0.56	ℓ	= 0.64 m
C_{G20}	= 0.81	θ_R	= 30°
h	= 0.30m	T	= 0.2
a	= 0.47m	b	= 1.10m

R_{G3} = 0.71W
R_{G4} = 0.21W

i.e. R_{G3} is almost 3 times its nominal value and R_{G4} is slightly less with very little load on wheels 1 and 2.

The inclusion of a compensating mechanism will introduce a vertical force between wheel 4 and the body which can be made some desired ratio of W $(C_G + T)$ and will increase R_{G4} and reduce R_{G3}.

The introduction of suspension springs makes the analysis more complicated in that applied forces will cause appreciable deflections and some form of computer based solution will be required.

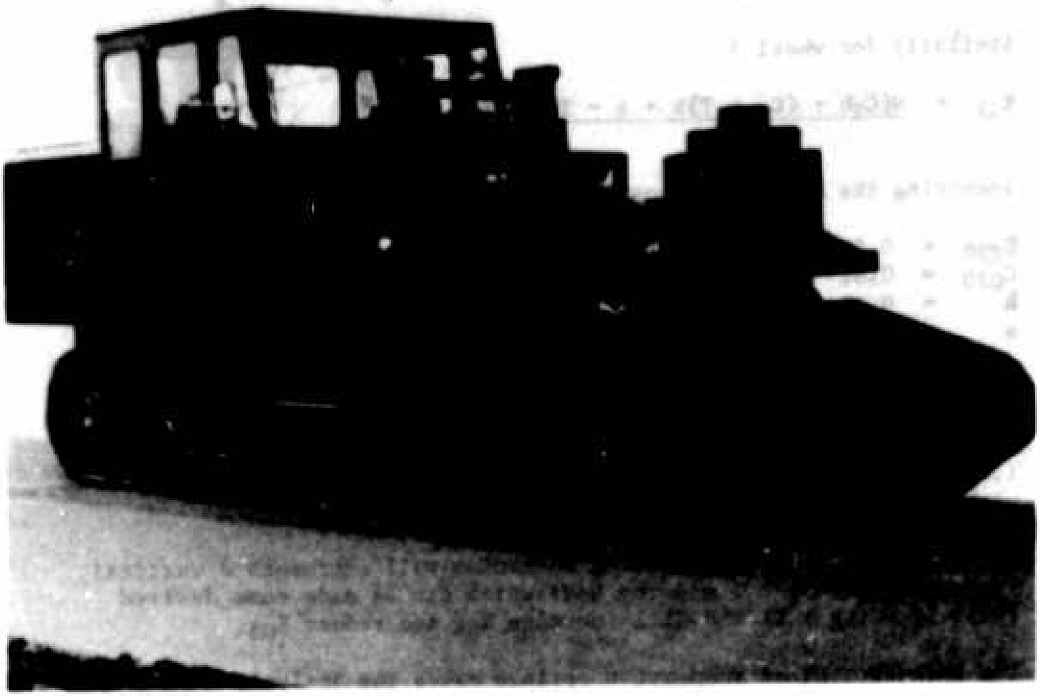


Fig 1 MVEE Mobile Tester with Track Rig

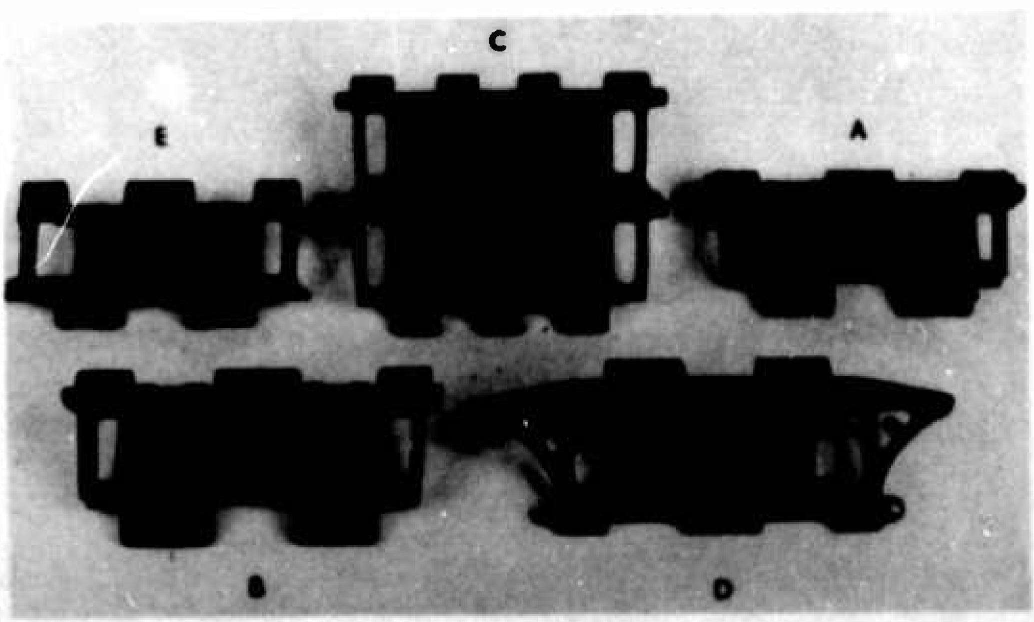
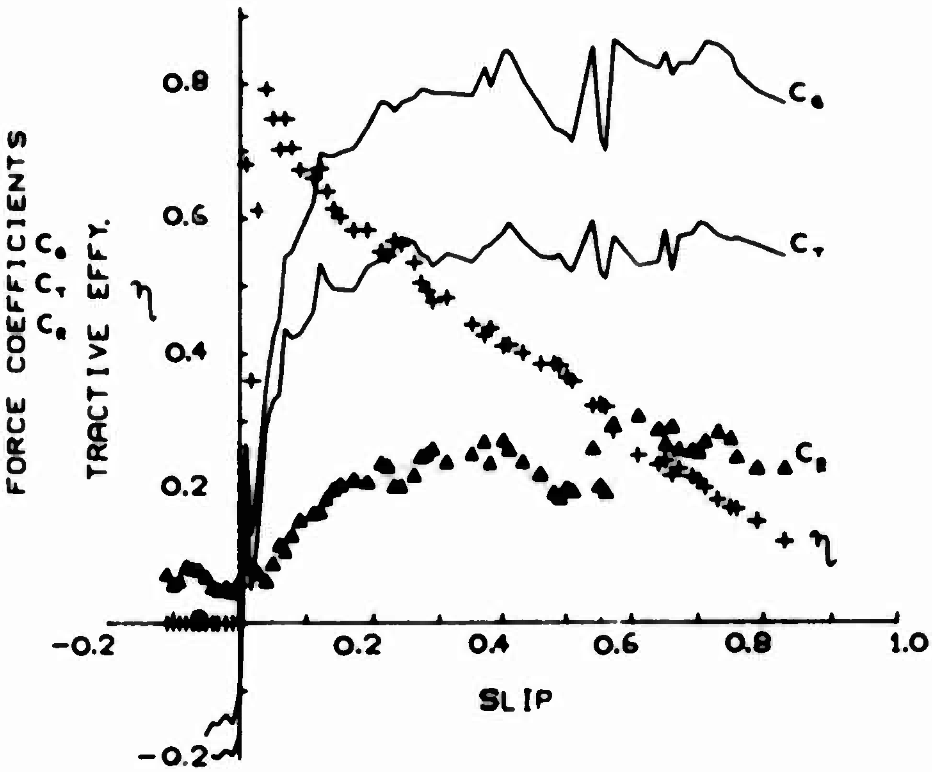
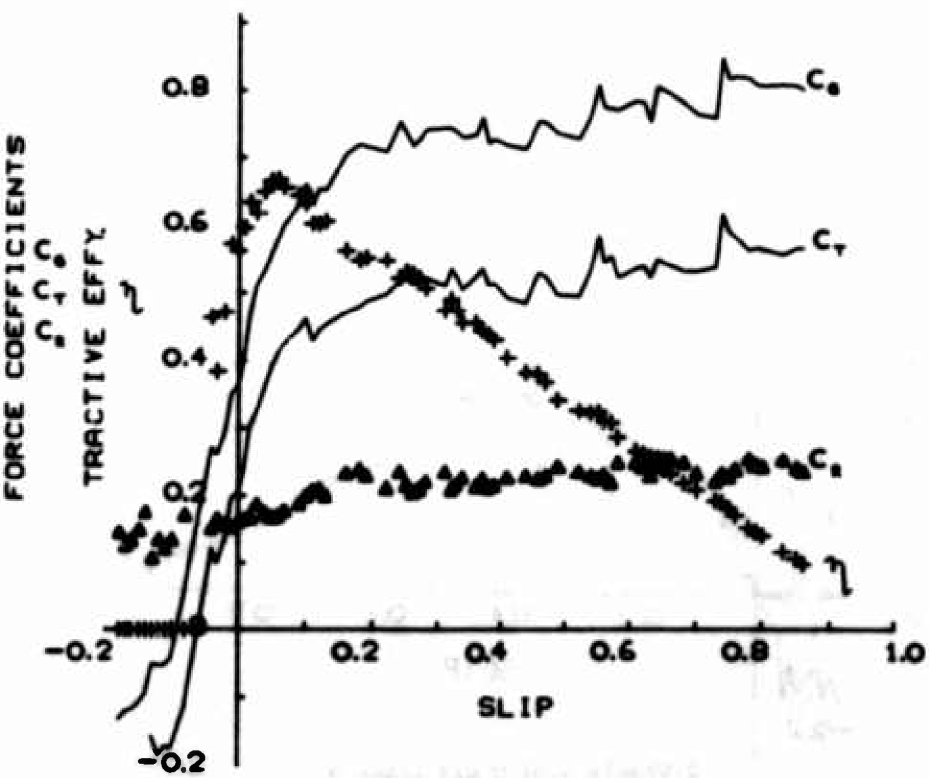


Fig 2 Track Links

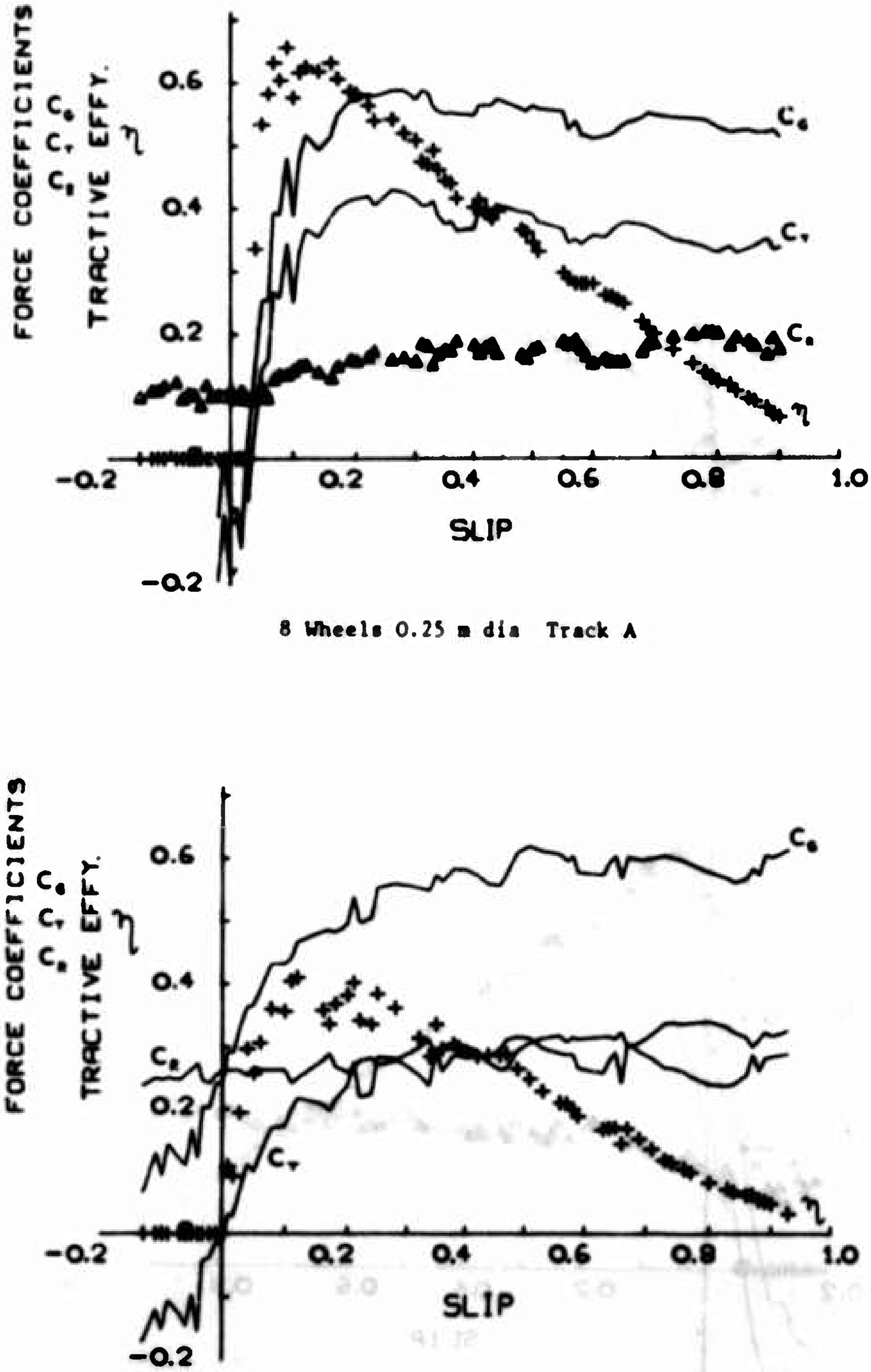


4 Wheels 0.61 m dia Track D



2 Wheels 0.61 m dia Track A

Fig 3 Typical Traction Curves Site A, 2 and 4 Wheel Configurations



8 Wheels 0.25 m dia Track A

2 Wheels 0.61 m dia Track A

Fig 4 Typical Traction Curves Site B, 2 and 8 Wheel Configurations

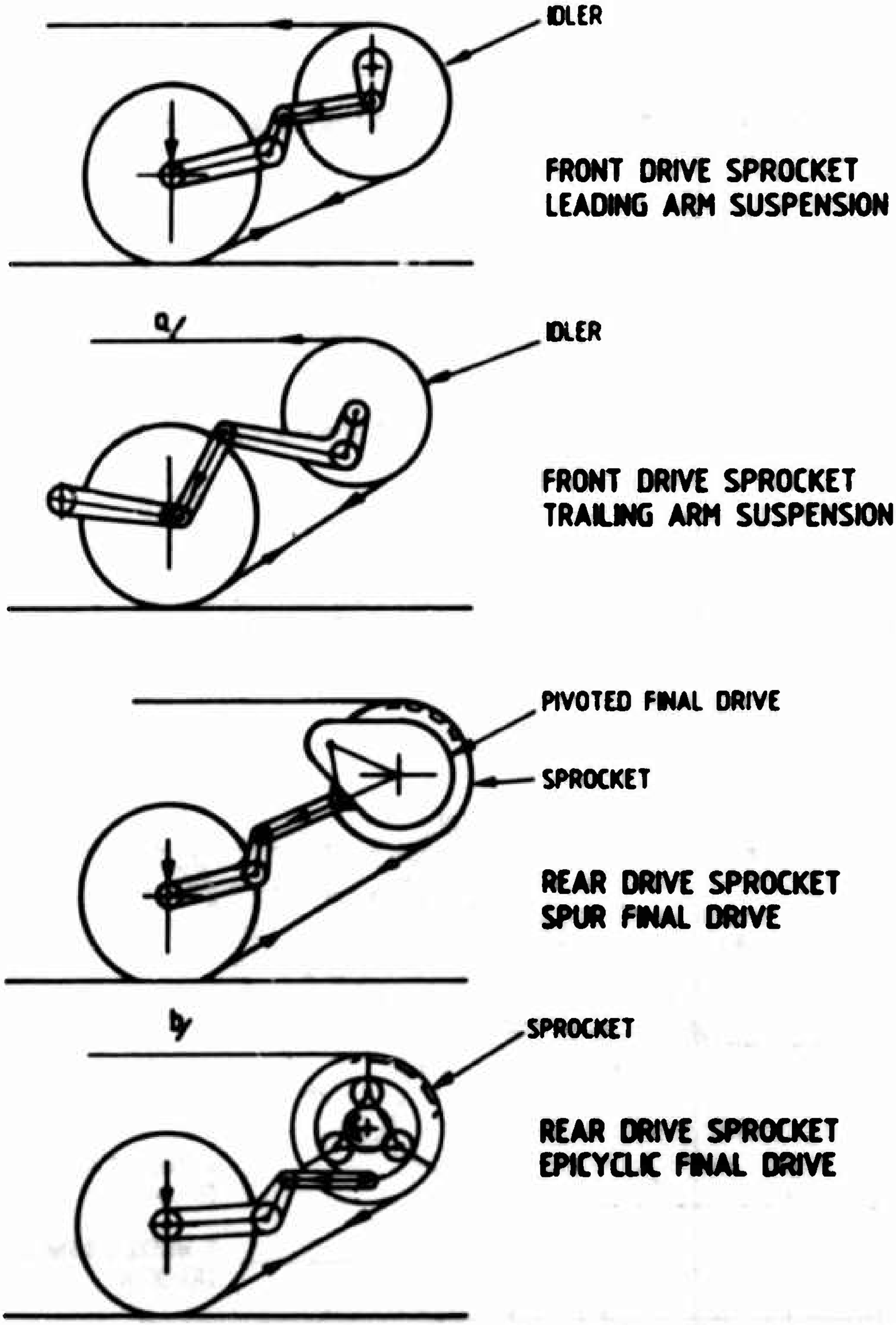
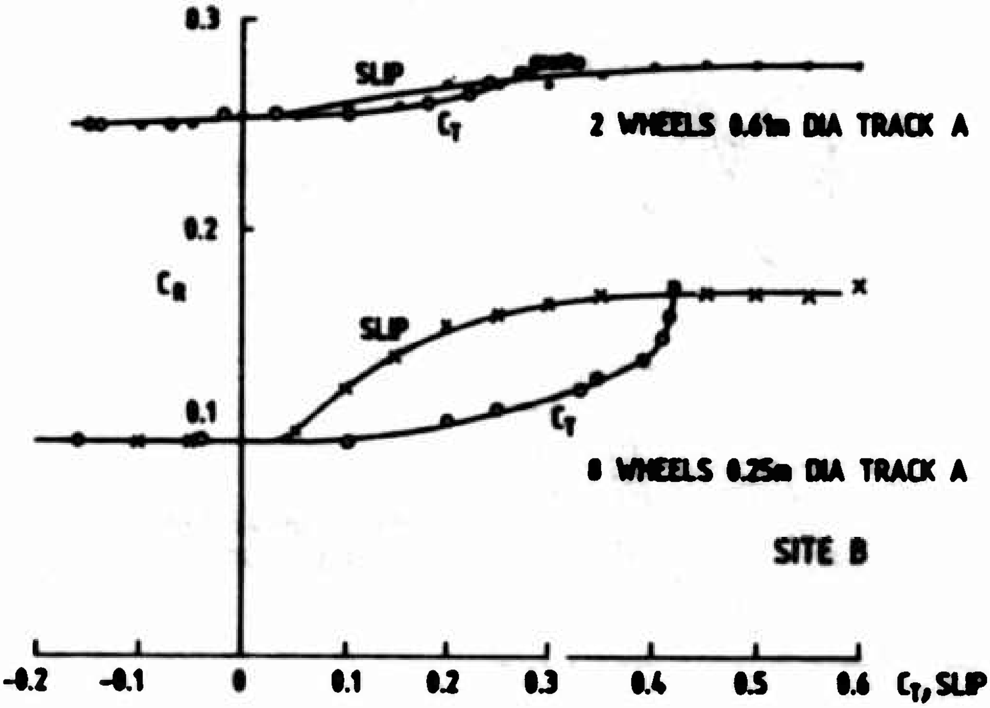


FIG 5 FORMS OF COMPENSATING MECHANISM FOR APPLYING DOWNFORCE ON REAR WHEEL



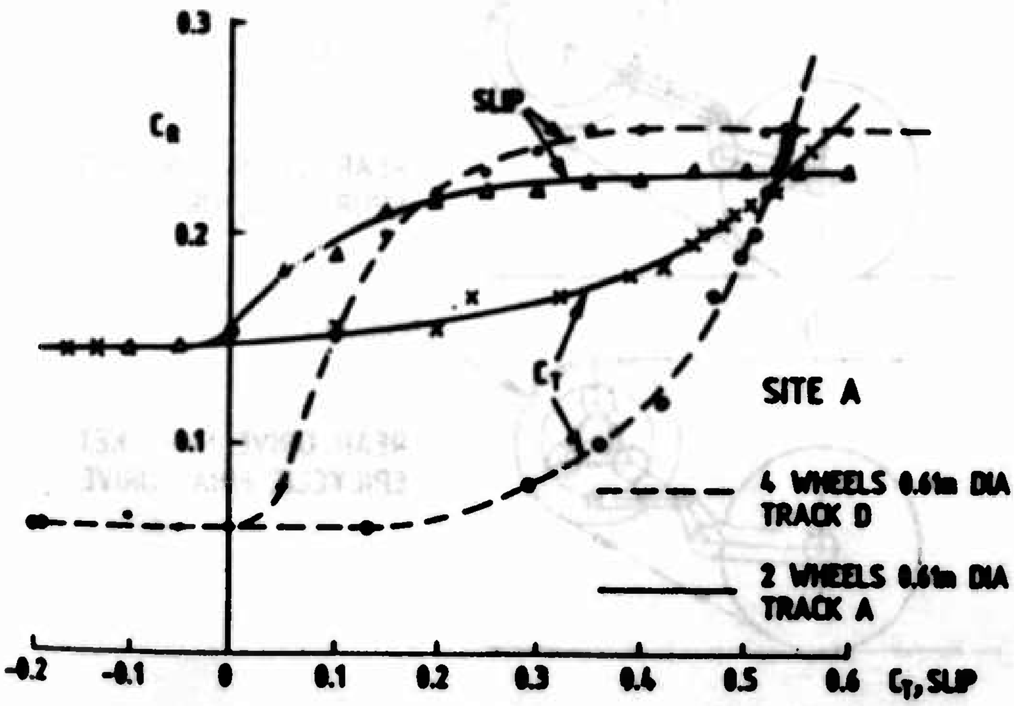


FIG 6
COEFFICIENT OF ROLLING RESISTANCE C_R PLOTTED AGAINST SLIP & COEFFICIENT OF TRACTION C_T FOR 2 and 4 WHEEL CONFIGURATIONS (SITE A) & 2 and 8 WHEEL CONFIGURATIONS (SITE B)

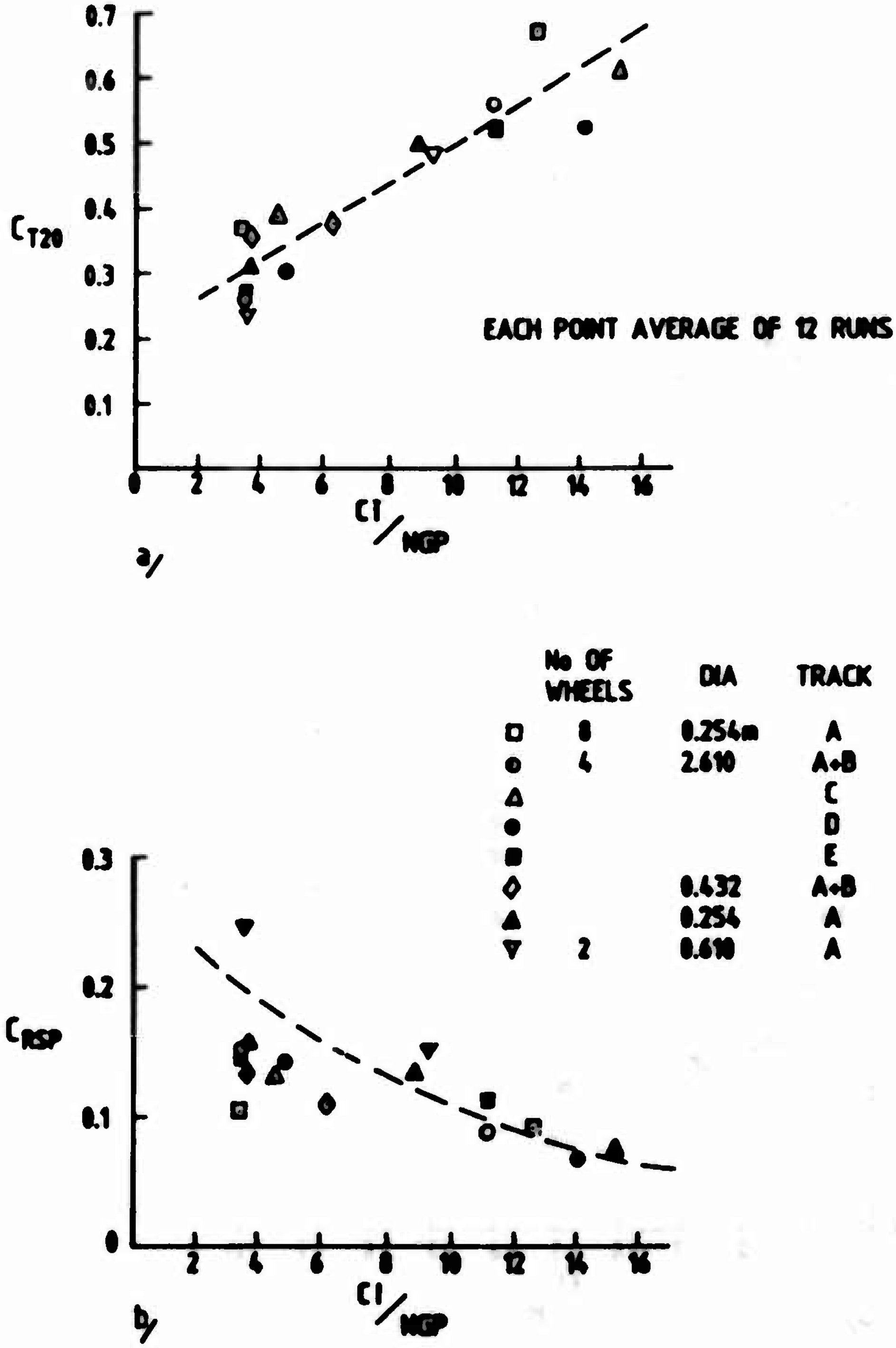


FIG 7

COEFFICIENT OF TRACTION AT 20% SLIP C_{T20} AND COEFFICIENT OF ROLLING RESISTANCE AT SELF PROPELLED POINT C_{RSP} PLOTTED AGAINST CONE INDEX OVER NOMINAL GROUND PRESSURE $^{CI}/_{NGP}$

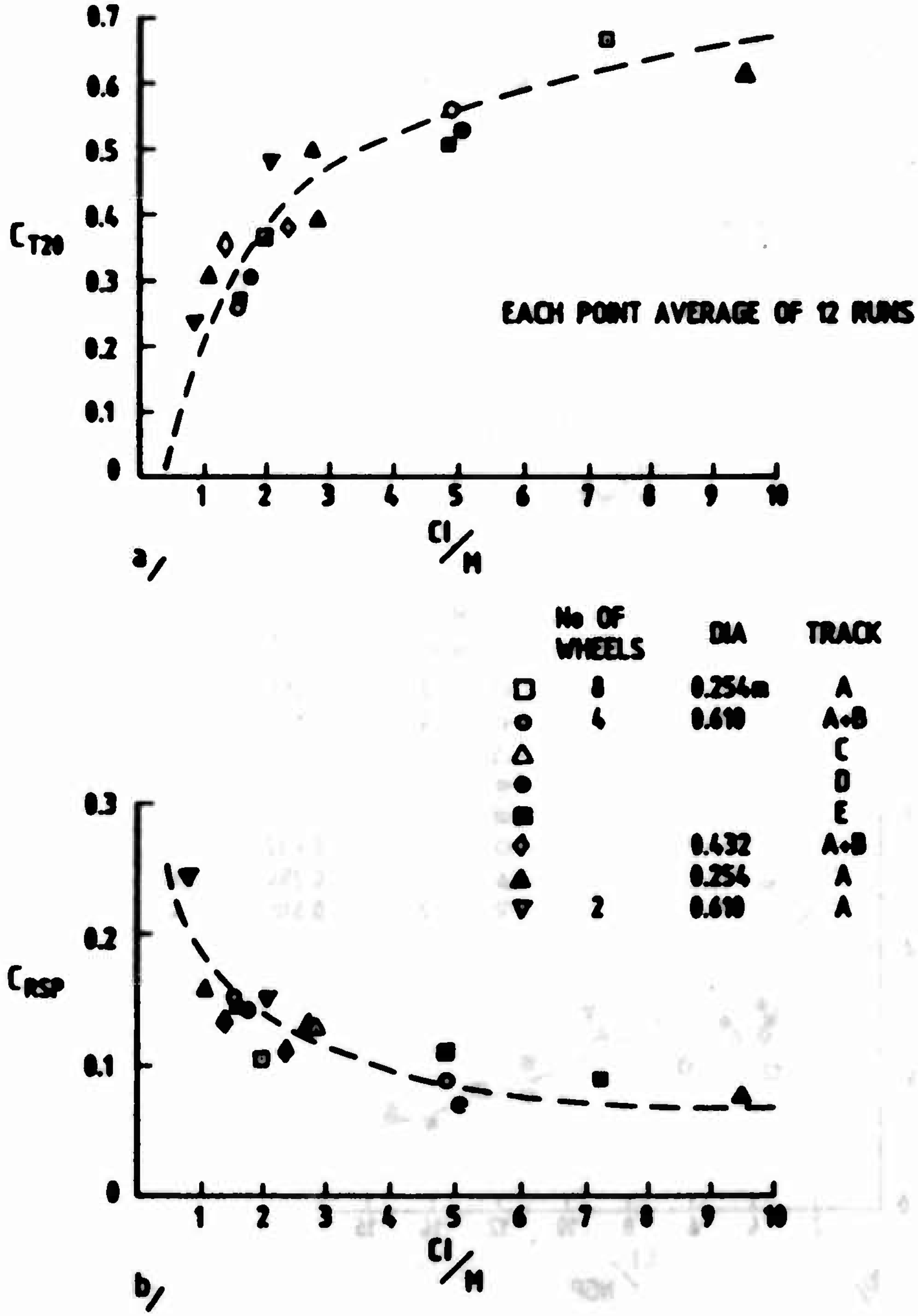


FIG 8
COEFFICIENT OF TRACTION AT 20% SLIP C_{T20} AND COEFFICIENT OF ROLLING RESISTANCE AT SELF PROPELLED POINT C_{RSP} PLOTTED AGAINST TRACK MOBILITY NUMBER CI/M

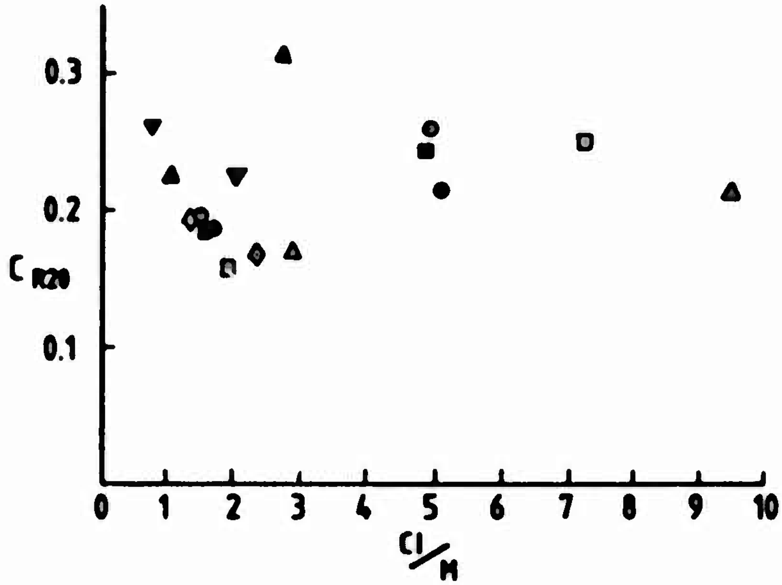


FIG 9 COEFFICIENT OF ROLLING RESISTANCE AT 20% SLIP C_{R20} PLOTTED AGAINST TRACK MOBILITY NUMBER $^{CI}/_{M}$

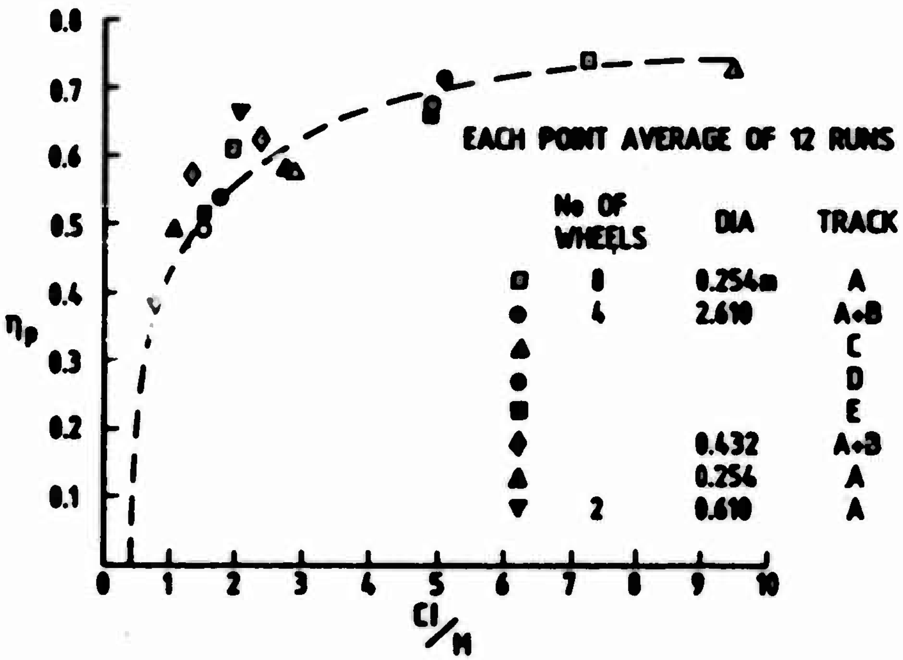


FIG 10 PEAK TRACTIVE EFFICIENCY η_p PLOTTED AGAINST TRACK MOBILITY NUMBER $^{CI}/_{M}$